Scope, Function Calls and Storage Management

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Adapted by Mooly Sagiv

Topics

- Block-structured languages and stack storage
- In-line Blocks
  - activation records
  - storage for local, global variables
- First-order functions
  - parameter passing
  - tail recursion and iteration
- Higher-order functions
  - deviations from stack discipline
  - language expressiveness => implementation complexity
- Garbage Collection

Block-Structured Languages

- Nested blocks, local variables
  - Example

new variables declared in nested blocks

outer block

```
{ int x = 2;
   { int y = 3;
      x = y+2;
   }
}
```

inner block

local variable

global variable

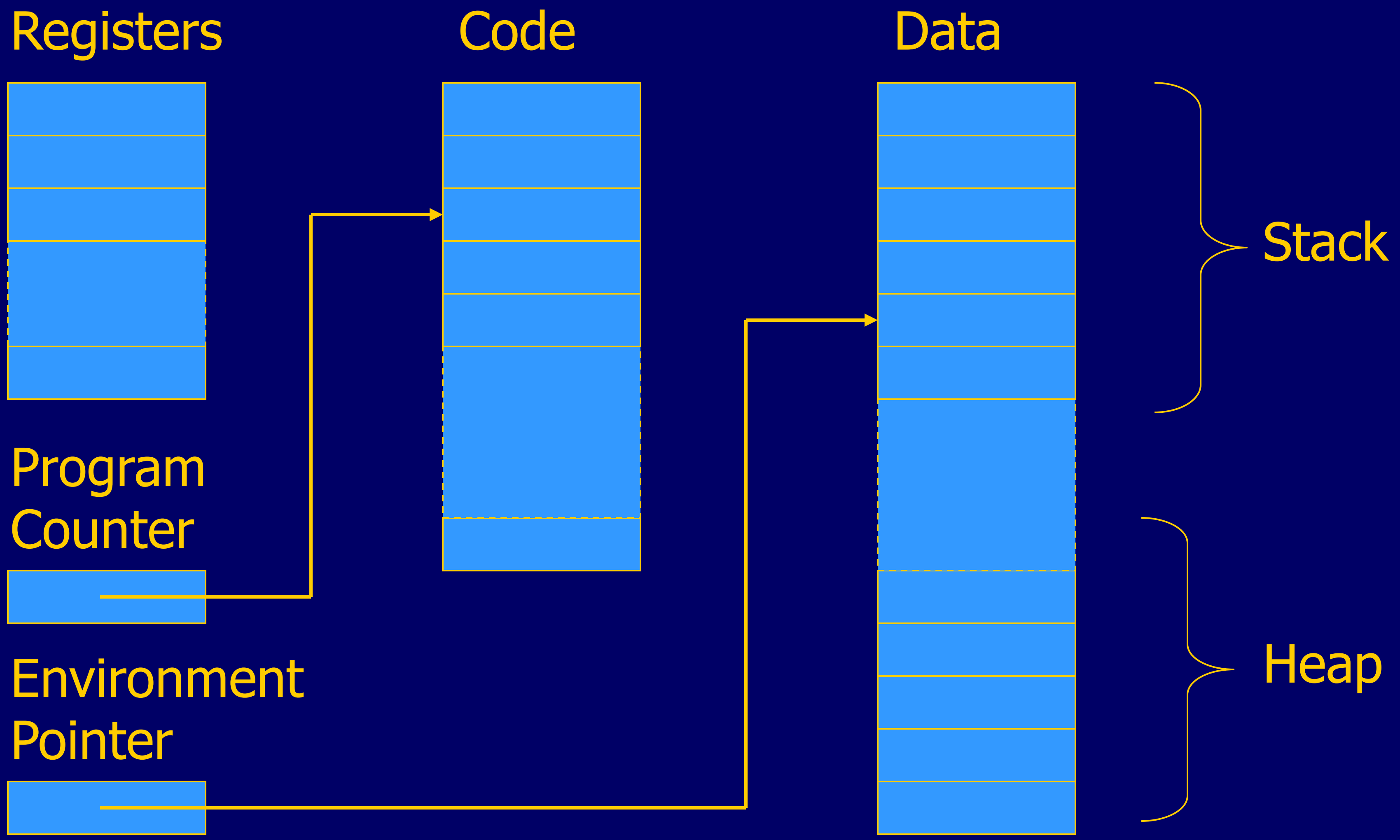
  - Storage management
    - Enter block: allocate space for variables
    - Exits block: some or all space may be deallocated

Examples

- Blocks in common languages
  - C, ~~JavaScript~~ *   { … }
  - Algol   begin … end
  - ML   let … in …
- Two forms of blocks
  - In-line blocks
  - Blocks associated with functions or procedures
- Topic: block-based memory management, access to local variables, parameters, global variables

* JavaScript functions provide blocks

Simplified Machine Model



Interested in Memory Mgmt Only

- Registers, Code segment, Program counter
  - Ignore registers
  - Details of instruction set will not matter
- Data Segment
  - Stack contains data related to block entry/exit
  - Heap contains data of varying lifetime
  - Environment pointer points to current stack position
    - Block entry: add new activation record to stack
    - Block exit: remove most recent activation record

Some basic concepts

- Scope
  - Region of program text where declaration is visible
- Lifetime (Duration)
  - Period of time when location is allocated to program

```
{ int x = … ;
    {  int y = … ;
        {  int x = … ;
           ….
        };
    };
};
```

- Inner declaration of x hides outer one.
- Called "hole in scope"
- Lifetime of outer x includes time when inner block is executed
- Lifetime ≠ scope
- Lines indicate "contour model" of scope.

In-line Blocks

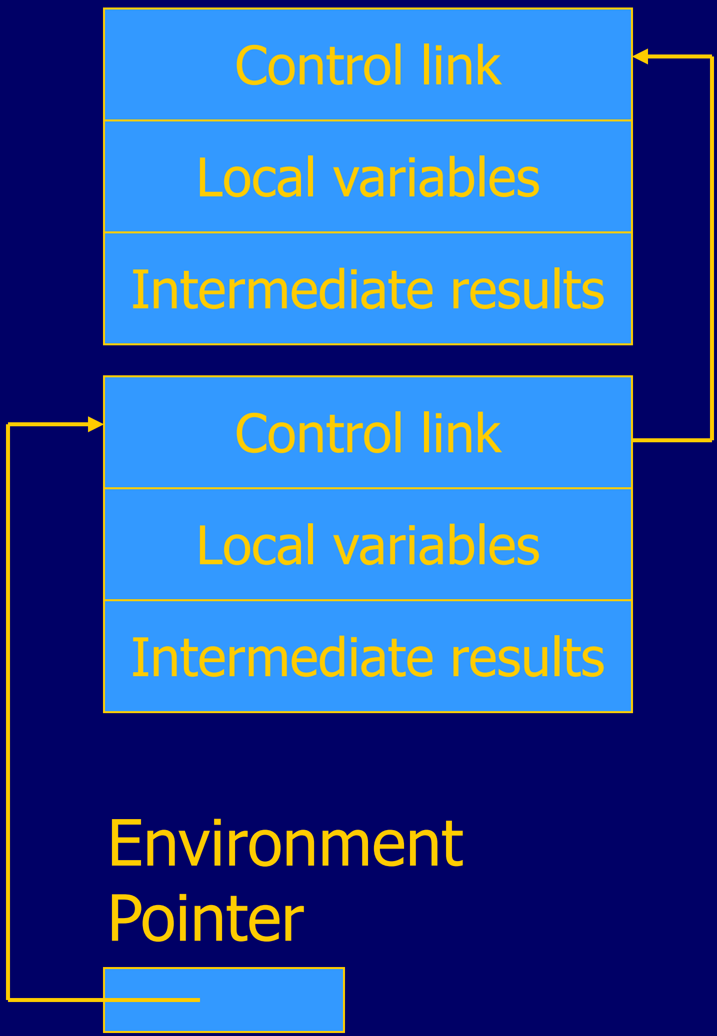
- Activation record
  - Data structure stored on run-time stack
  - Contains space for local variables
- Example

```
{ int x=0;
  int y=x+1;
    {  int z=(x+y)*(x-y);
     };
};
```

Push record with space for x, y
Set values of x, y
    Push record for inner block
    Set value of z
    Pop record for inner block
Pop record for outer block

May need space for variables and intermediate results like (x+y), (x-y)

Activation record for in-line block



- Control link
  - pointer to previous record on stack
- Push record on stack:
  - Set new control link to point to old env ptr
  - Set env ptr to new record
- Pop record off stack
  - Follow control link of current record to reset environment pointer

Can be optimized away, but assume not for purpose of discussion.

Example

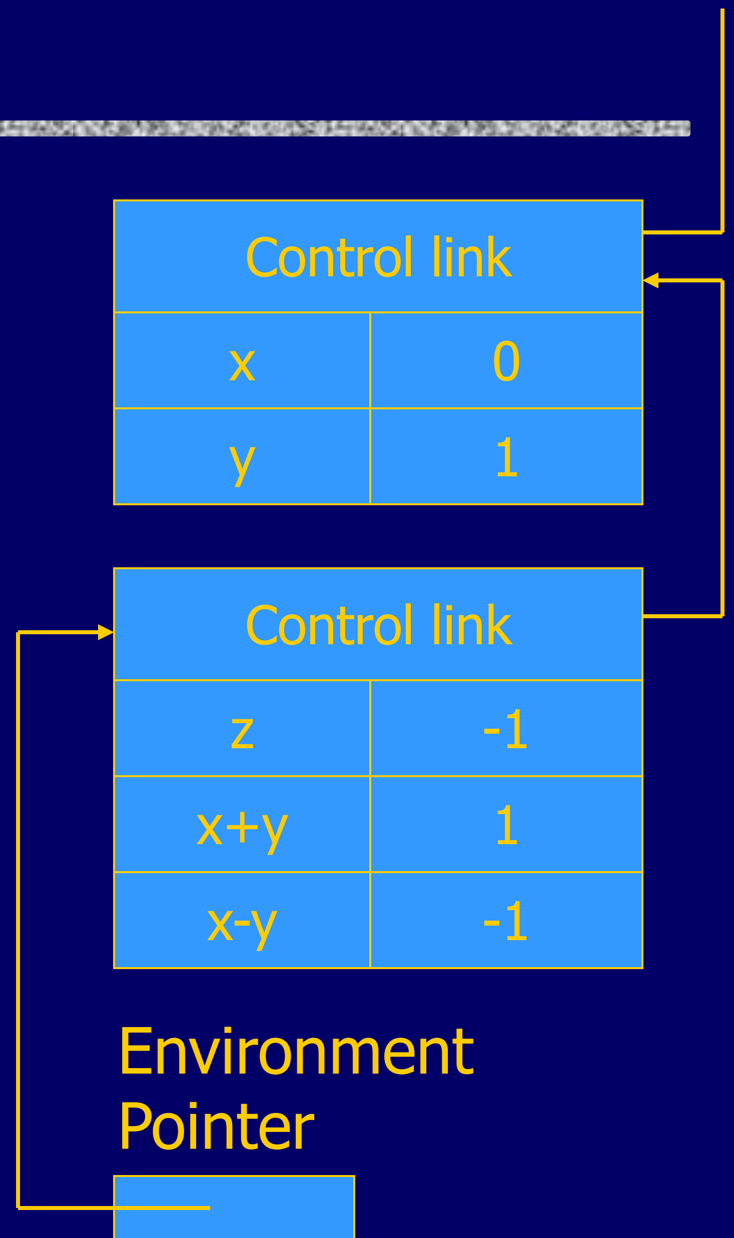
```
{ int x=0;
  int y=x+1;
    { int z=(x+y)*(x-y);
    };
};
```

Push record with space for x, y

Set values of x, y

- Push record for inner block
- Set value of z
- Pop record for inner block

Pop record for outer block



Scoping rules

- Global and local variables
  - x, y are local to outer block
  - z is local to inner bock
  - x, y are global to inner block

```
{ int x=0;
   int y=x+1;
      {  int z=(x+y)*(x-y);
       };
};
```

- Static scope
  - global refers to declaration in closest enclosing block
- Dynamic scope
  - global refers to most recent activation record

These are same until we consider function calls.

Functions and procedures

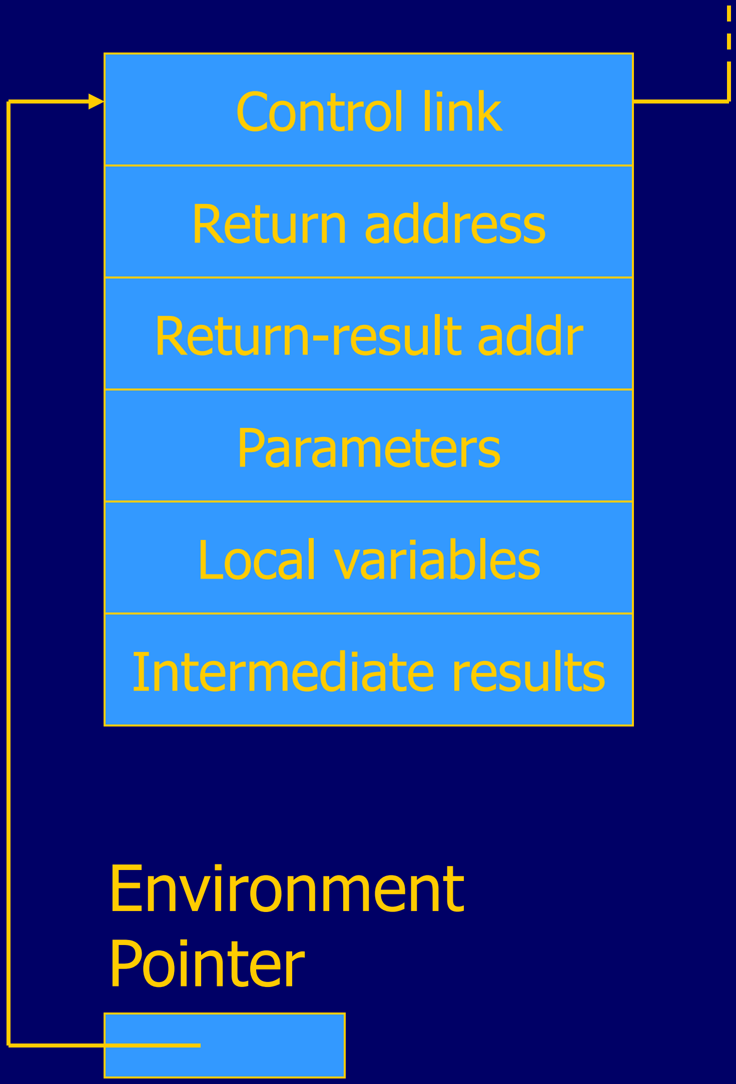
- Syntax of procedures (Algol) and functions (C)

```
procedure P (<pars>)
    begin
        <local vars>
        <proc body>
    end;
```

```
<type> function f(<pars>)
{
        <local vars>
        <function body>
}
```

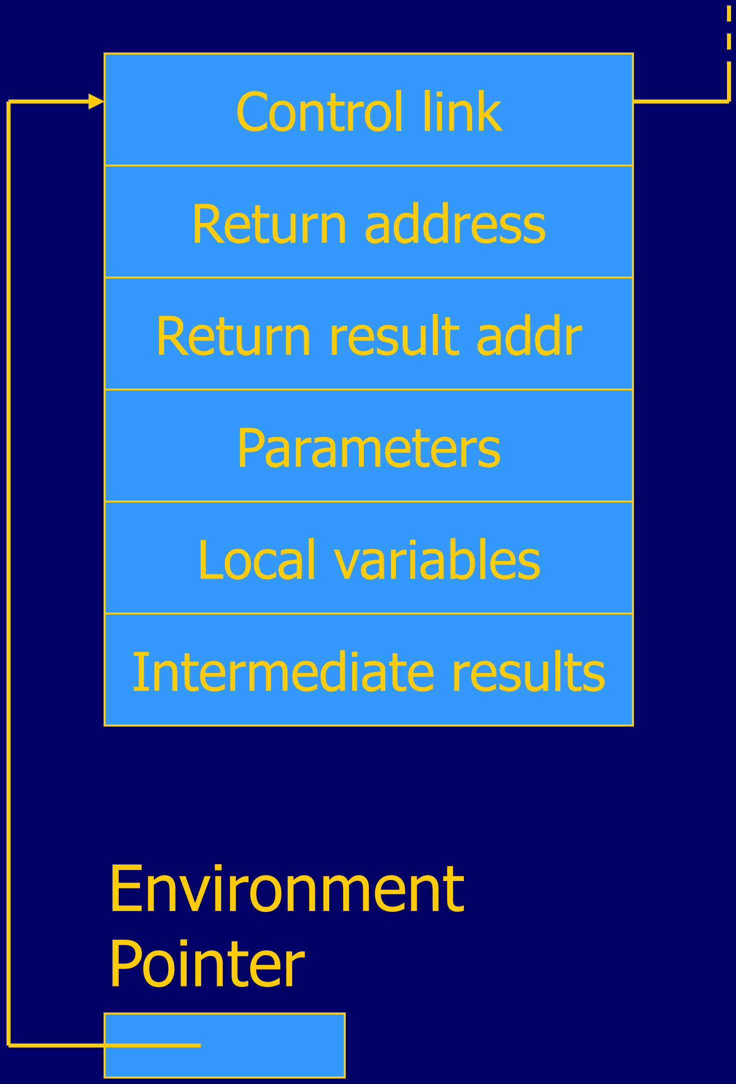
- Activation record must include space for
  - parameters
  - return address
  - local variables, intermediate results
  - return value (an intermediate result)
  - location to put return value on function exit

Activation record for function



- **Return address**
  - Location of code to execute on function return
- **Return-result address**
  - Address in activation record of calling block to receive return address
- **Parameters**
  - Locations to contain data from calling block

Example



- **Function**

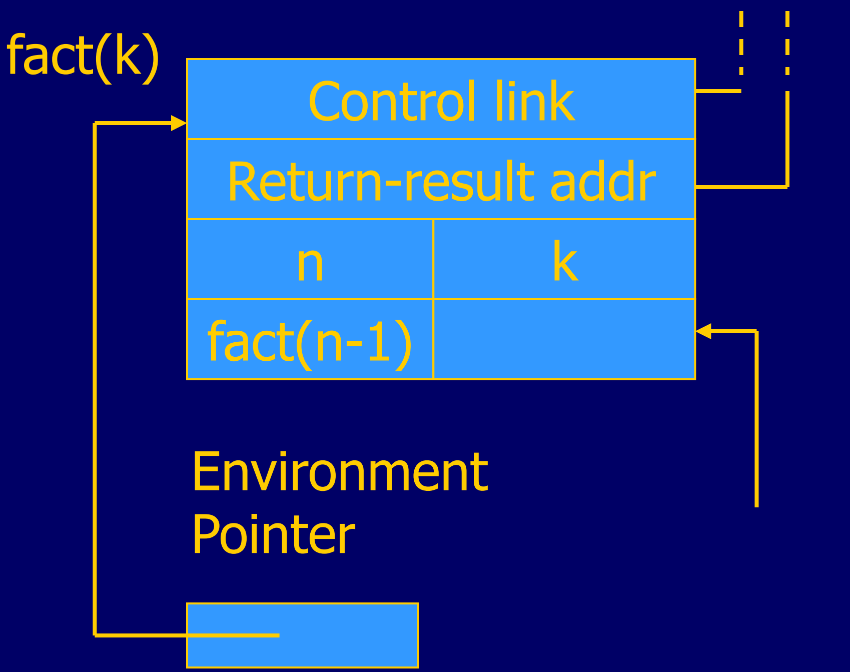
  fact(n) = if n<= 1 then 1
  else n * fact(n-1)

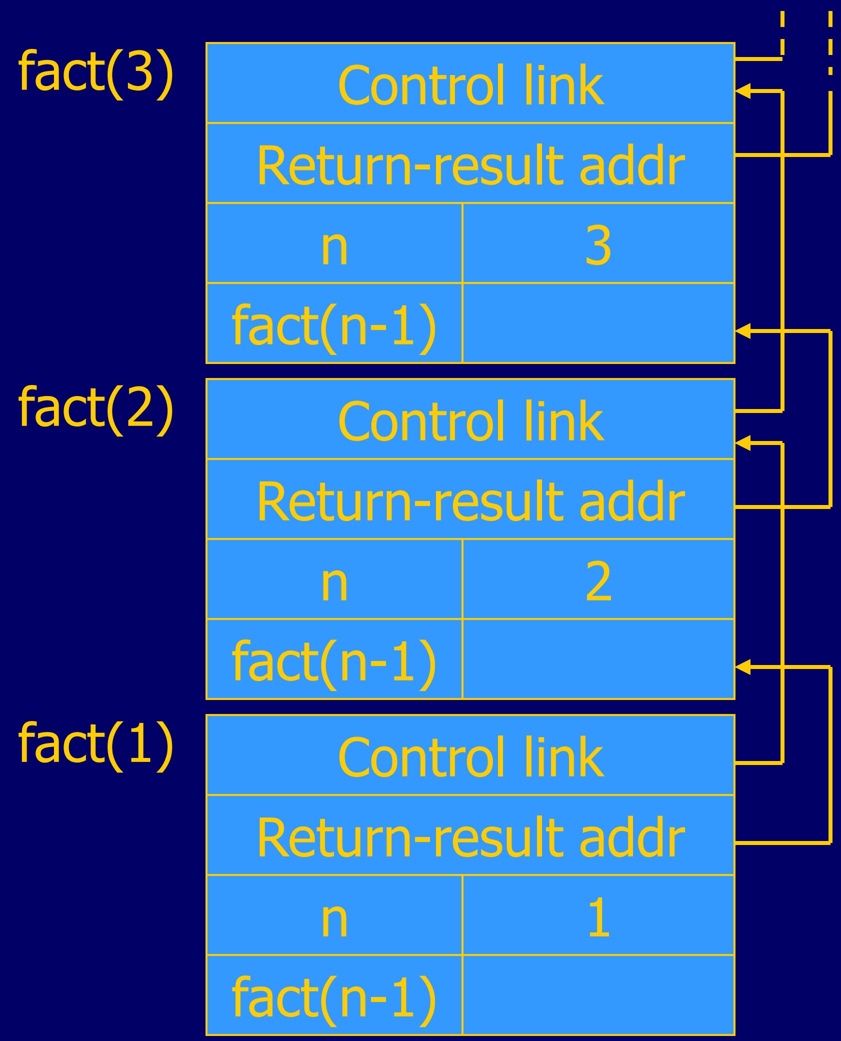
  - Return result address
  - location to put fact(n)

- **Parameter**
  - set to value of n by calling sequence

- **Intermediate result**
  - locations to contain value of fact(n-1)

Function call



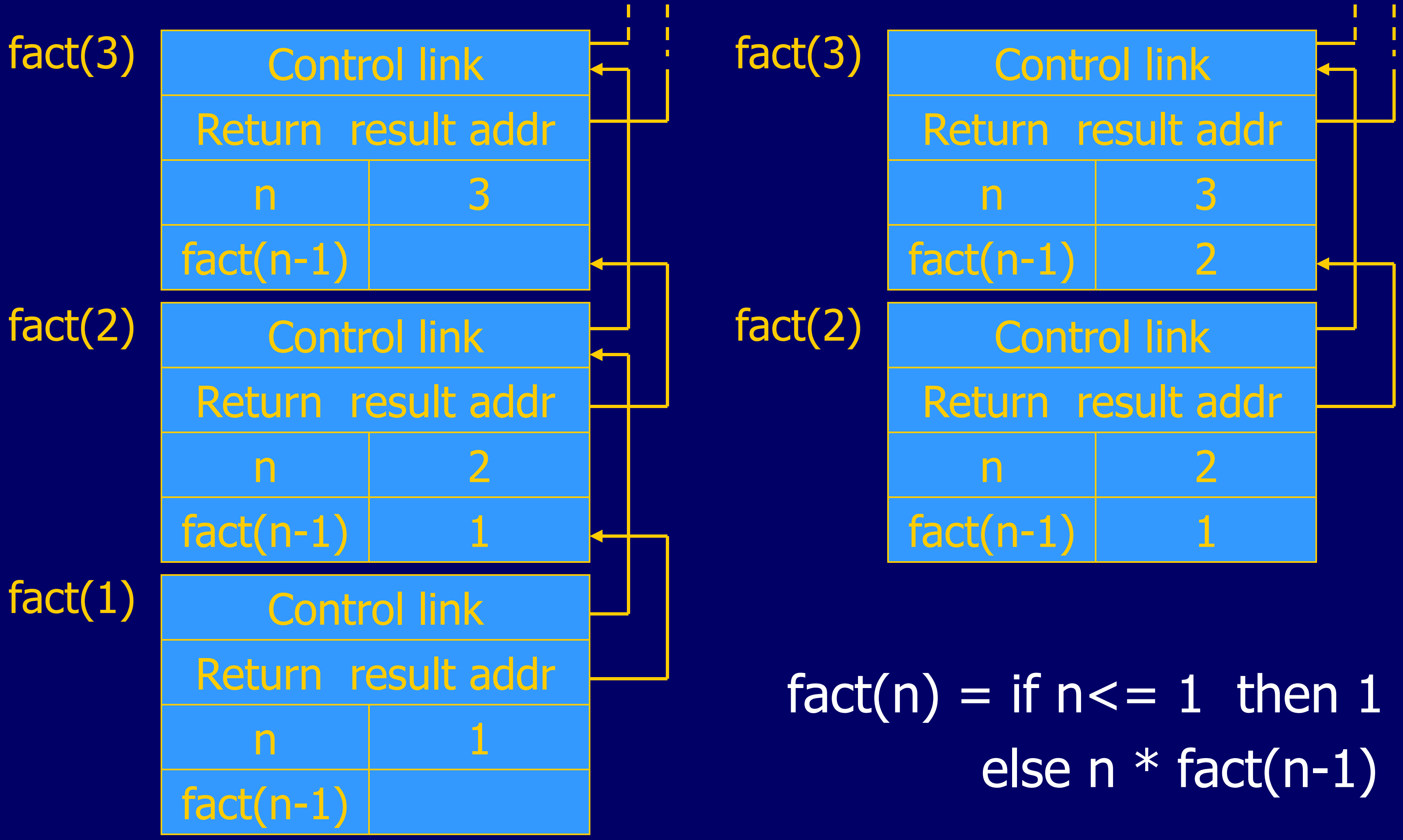


fact(n) = if n<= 1 then 1
else n * fact(n-1)

Return address omitted; would be ptr into code segment

Function return next slide →

Function return



fact(n) = if n<= 1 then 1
else n * fact(n-1)

Topics for first-order functions

- Parameter passing
  - pass-by-value: copy value to new activation record
  - pass-by-reference: copy ptr to new activation record
- Access to global variables
  - global variables are contained in an activation record higher “up” the stack
- Tail recursion
  - an optimization for certain recursive functions

See this yourself: write factorial and run under debugger

L-values vs. R-values

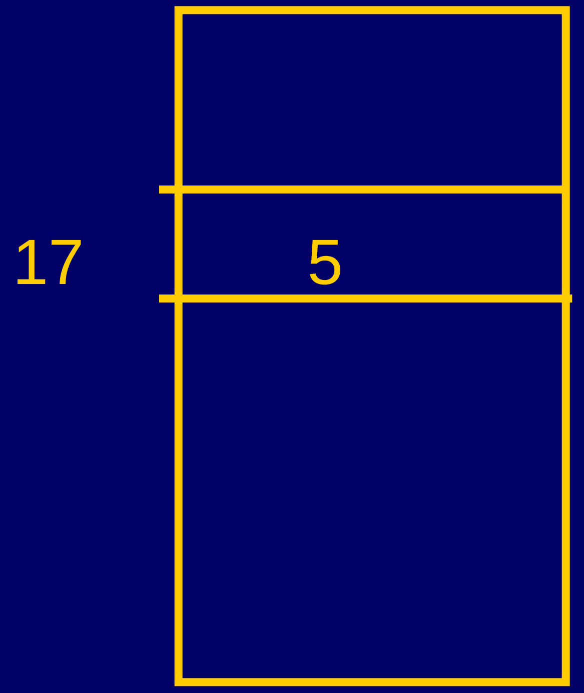
- Assignment x := exp is compiled into:
  - Compute the **address** of x
  - Compute the **value** of exp
  - Store the value of exp into the address of x
- Generalization
  - R-value
    - Maps program expressions into Context values
  - L-value
    - Maps program expressions into locations
    - Not always defined
  - Java has no small L-values

A Simple Example

int x = 5;

x = x + 1;

Runtime memory



A Simple Example

int x = 5;

lvalue(x)=17, rvalue(x) =5

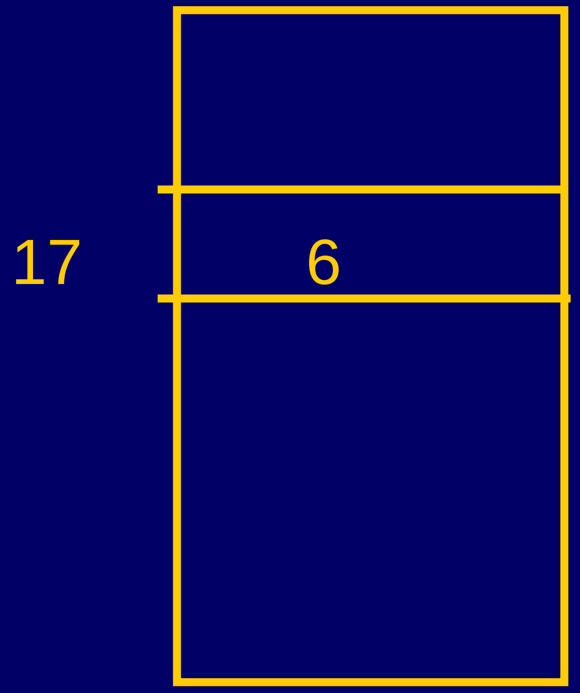
lvalue(5)=⊥, rvalue(5)=5

x = x + 1;

lvalue(x)=17, rvalue(x) =5

lvalue(5)=⊥, rvalue(5)=5

Runtime memory



Partial rules for Lvalue in C

- Type of e is pointer to T
- Type of e1 is integer
- lvalue(e2) $\neq$undefined

```
{ int a[100];
*(a + 5) = 8
}
```

exp	**lvalue**	**rvalue**
id	location(id)	content(location(id))
const	undefined	value(const)
***e**	rvalue(e)	content(rvalue(e))
&e2	undefined	lvalue(e2)
e + e1	undefined	rvalue(e)+sizeof(T)*rvalue(e1)

Parameter passing

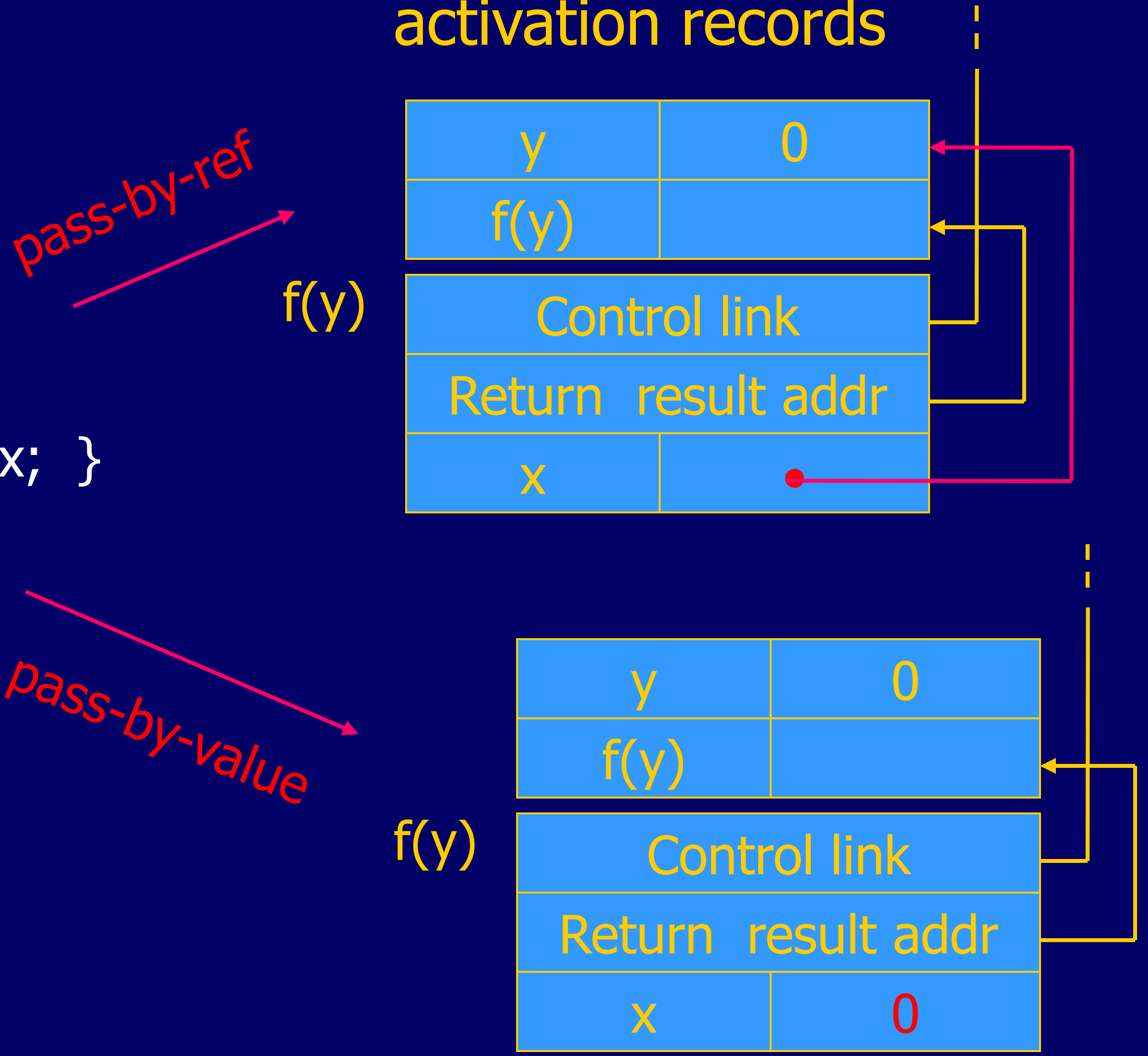
- Pass-by-reference
  - Place L-value (address) in activation record
  - Function can assign to variable that is passed
- Pass-by-value
  - Place R-value (contents) in activation record
  - Function cannot change value of caller’s variable
  - Reduces aliasing (alias: two names refer to same loc)

Example

pseudo-code

```
function f (x) =
    { x = x+1; return x;  }
var y = 0;
print (f(y)+y);
```

activation records



Access to global variables

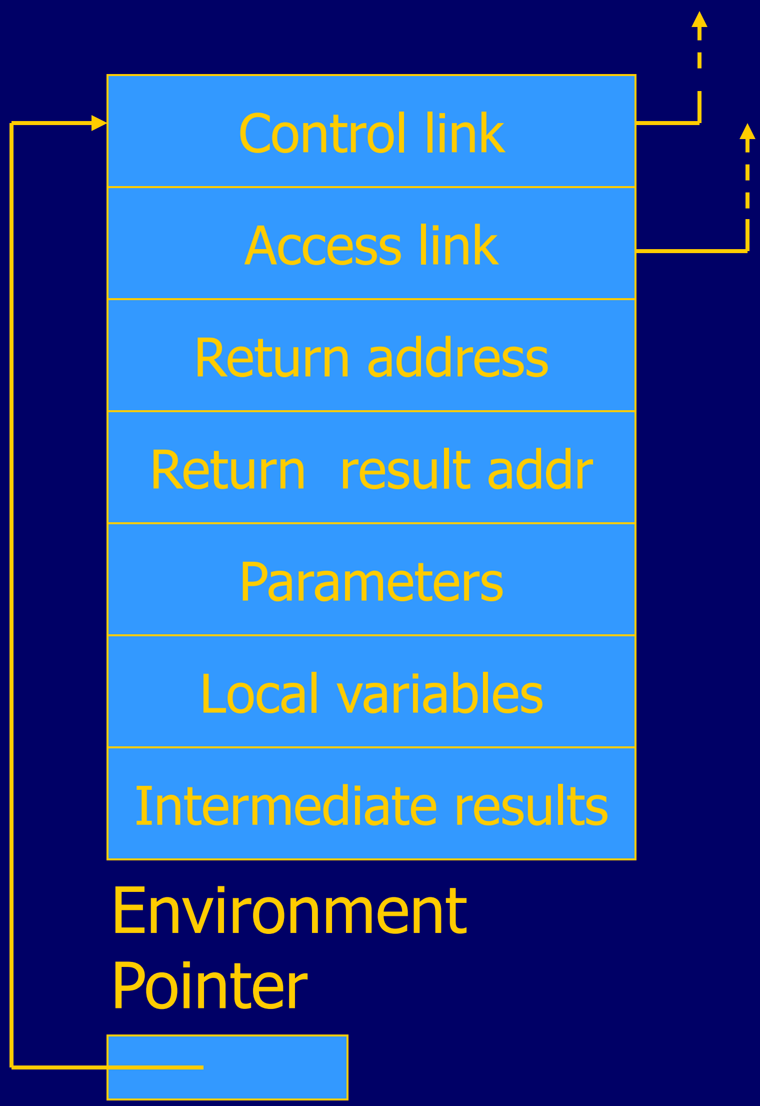
- Two possible scoping conventions
  - Static scope: refer to closest enclosing block
  - Dynamic scope: most recent activation record on stack
- Example

```
var x=1;
function g(z) { return x+z; }
function f(y) {
    var x = y+1;
    return g(y*x);
}
f(3);
```

outer block	x	1
f(3)	y	3
	x	4
g(12)	z	12

Which x is used for expression x+z ?

Activation record for static scope



- Control link
  - Link to activation record of previous (calling) block
- Access link
  - Link to activation record of closest enclosing block in program text
- Difference
  - Control link depends on dynamic behavior of prog
  - Access link depends on static form of program text

Complex nesting structure

```
function m(…) {
   var x=1;
   …
   function n( … ){
     function g(z) { return x+z; }
     …
     { …
          function f(y) {
             var x = y+1;
             return g(y*x); }
        …
       f(3);  … }
   … n( … ) …}
 … m(…)
```

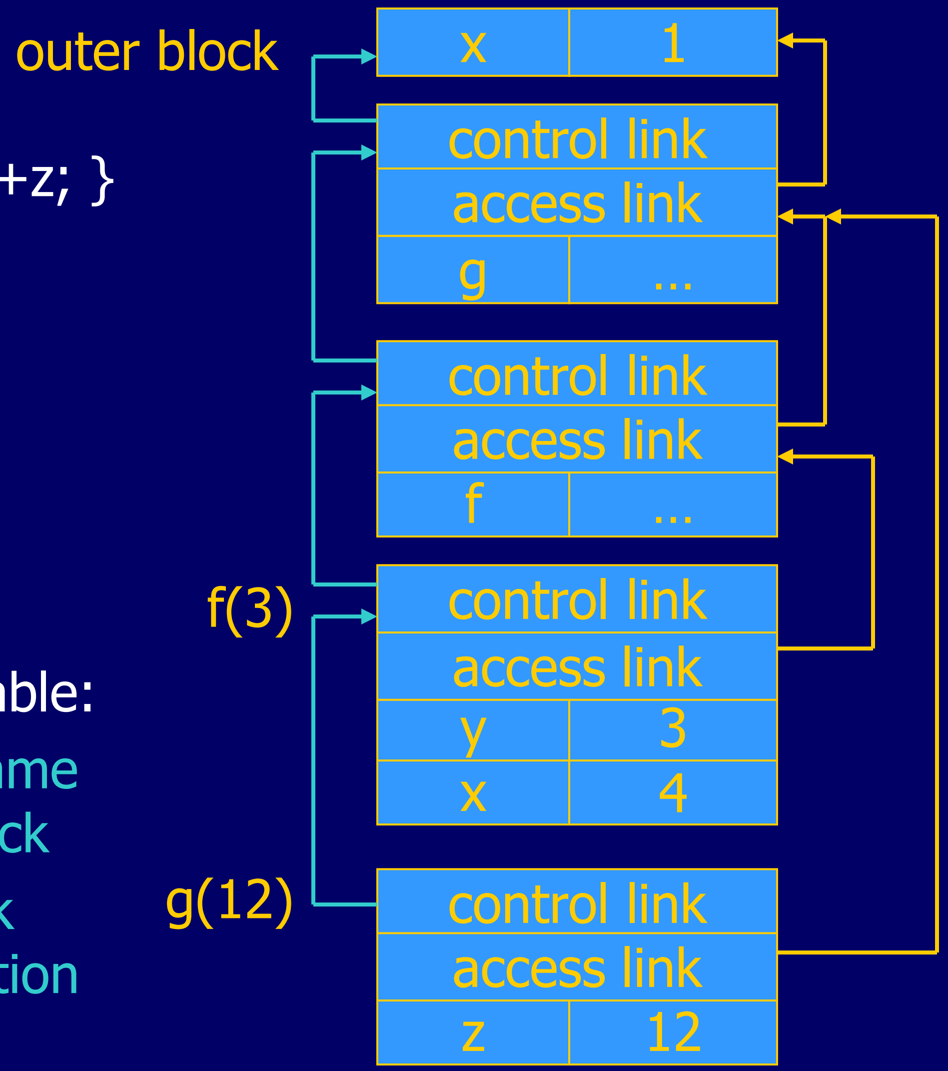
Simplify to

```
var x=1;
   function g(z) { return x+z; }
        function f(y)
          { var x = y+1;
             return g(y*x); }
       f(3);
```

Simplified code has same block nesting, if we follow convention that each declaration begins a new block.

Static scope with access links

```
var x=1;
  function g(z) = { return x+z; }
    function f(y) =
      { var x = y+1;
        return g(y*x); }
    f(3);
```



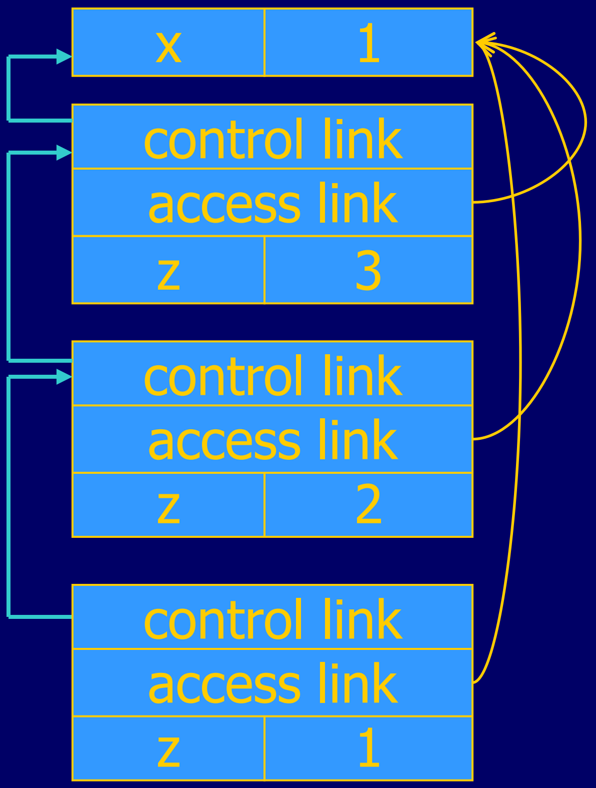
Use access link to find global variable:

- Access link is always set to frame of closest enclosing lexical block
- For function body, this is block that contains function declaration

Static scope with access links & recursion

```
var x=1;
  function fac(z) = {
    if z = 1 then return x;
             else return z * fac(z-1);
  }

fac(3)
```



Tail recursion (first-order case)

- Function g makes a *tail call* to function f if
  - Return value of function f is return value of g
- Example

tail call　　　　not a tail call

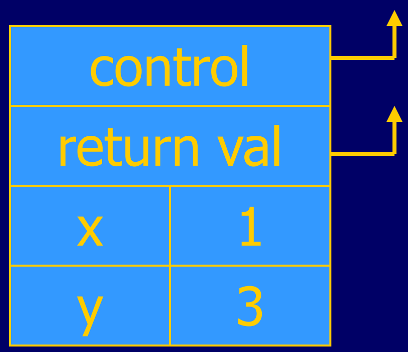
fun g(x) = if x>0 then f(x) else f(x)*2

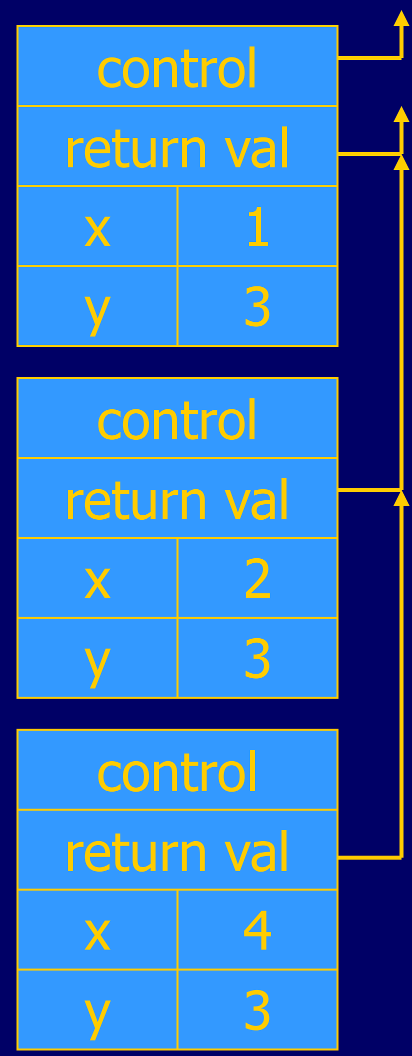
- Optimization
  - Can pop activation record on a tail call
  - Especially useful for recursive tail call
    - next activation record has exactly same form

Example

Calculate least power of 2 greater than y

f(1,3)






```
fun f(x,y) = if x>y
      then x
      else f(2*x, y);
f(1,3) + 7;
```

Optimization

- Set return value address to that of caller

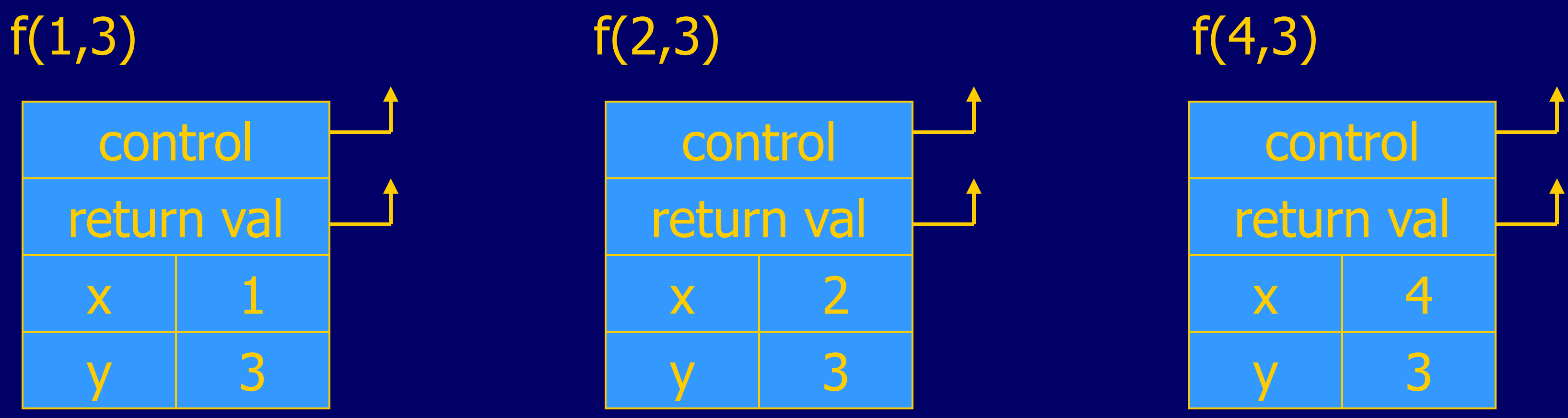
Question

- Can we do the same with control link?

Optimization

- avoid return to caller

Tail recursion elimination




```
fun f(x,y) = if x>y
      then x
      else f(2*x, y);
f(1,3);
```

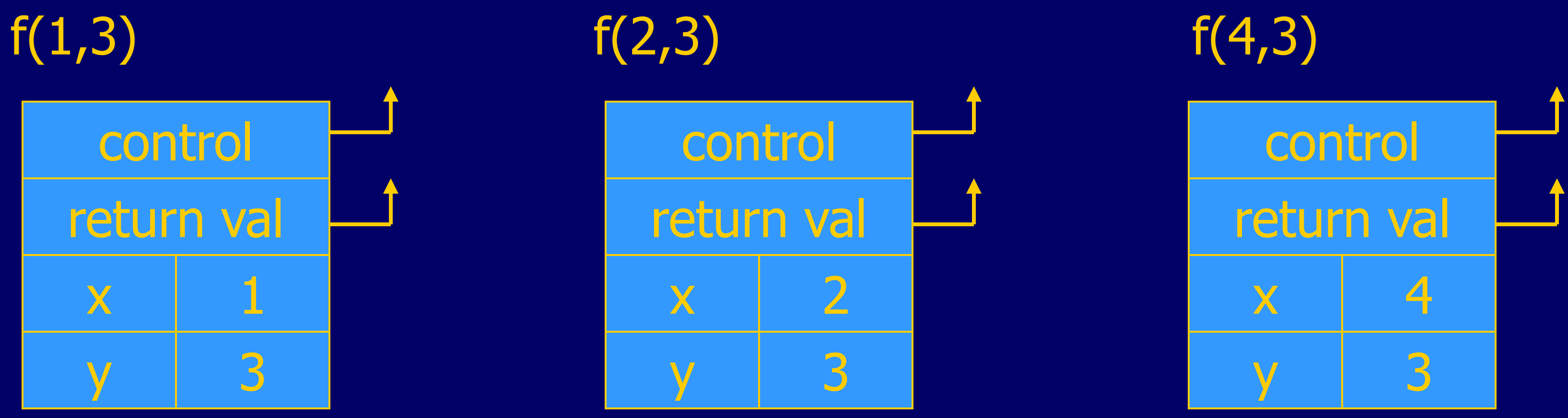
Optimization

- pop followed by push = reuse activation record in place

Conclusion

- Tail recursive function equiv to iterative loop

Tail recursion and iteration




```
fun f(x,y) = if x>y
      then x
      else f(2*x, y);
f(1,y);
```

```
function g(y) {
   var x = 1;
   while (!x>y)
      x = 2*x;
   return x;
}
```

test

loop body

initial value

Higher-Order Functions

- Language features
  - Functions passed as arguments
  - Functions that return functions from nested blocks
  - Need to maintain environment of function
- Simpler case
  - Function passed as argument
  - Need pointer to activation record “higher up” in stack
- More complicated second case
  - Function returned as result of function call
  - Need to keep activation record of returning function

Pass function as argument

OCaml

```
let x = 4 in
  let f = fun y -> x*y in
    let g = fun h ->
             let x=7
              in
              h(3) + x
      in
    g(f)
```

Pseudo-JavaScript

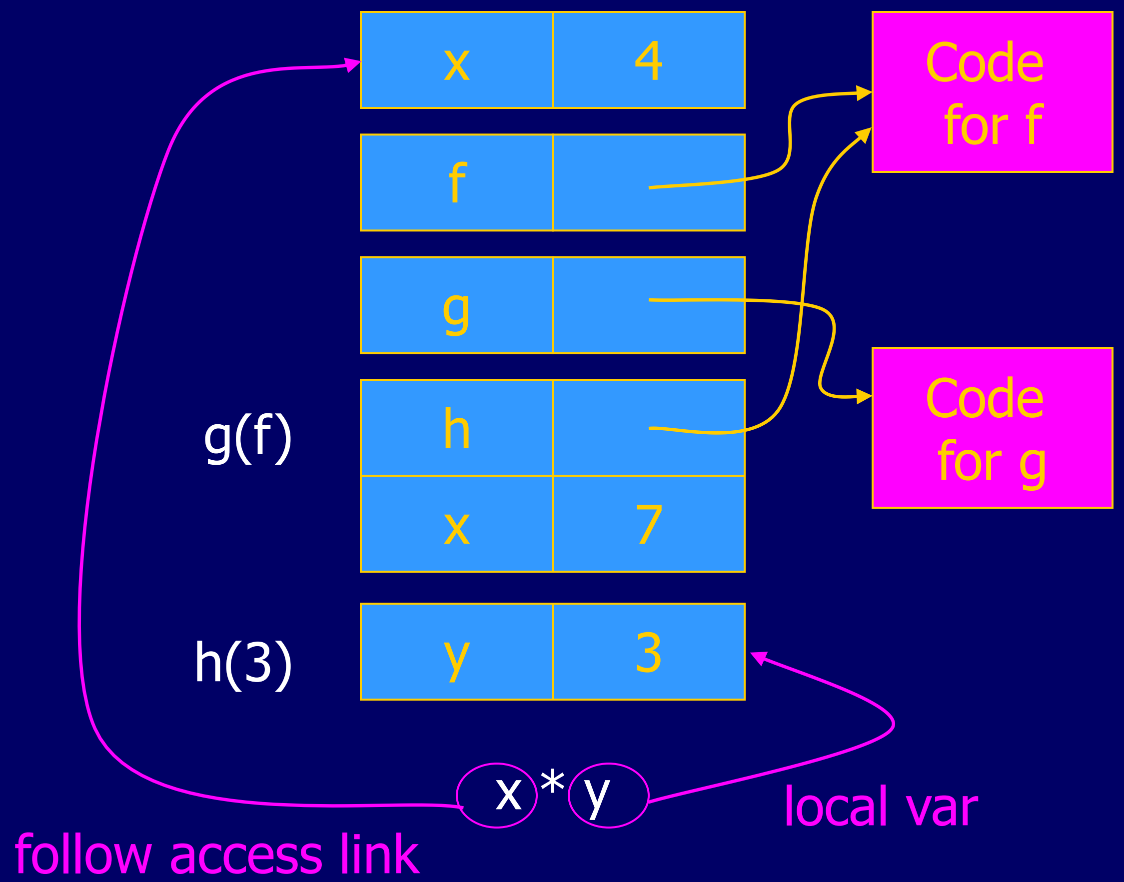
```
{ var x = 4;
  { function f(y) {return x*y};
    { function g(h) {
          var x = 7;
          return h(3) + x;
      };
      g(f);
} } }
```

There are two declarations of x

Which one is used for each occurrence of x?

Static Scope for Function Argument

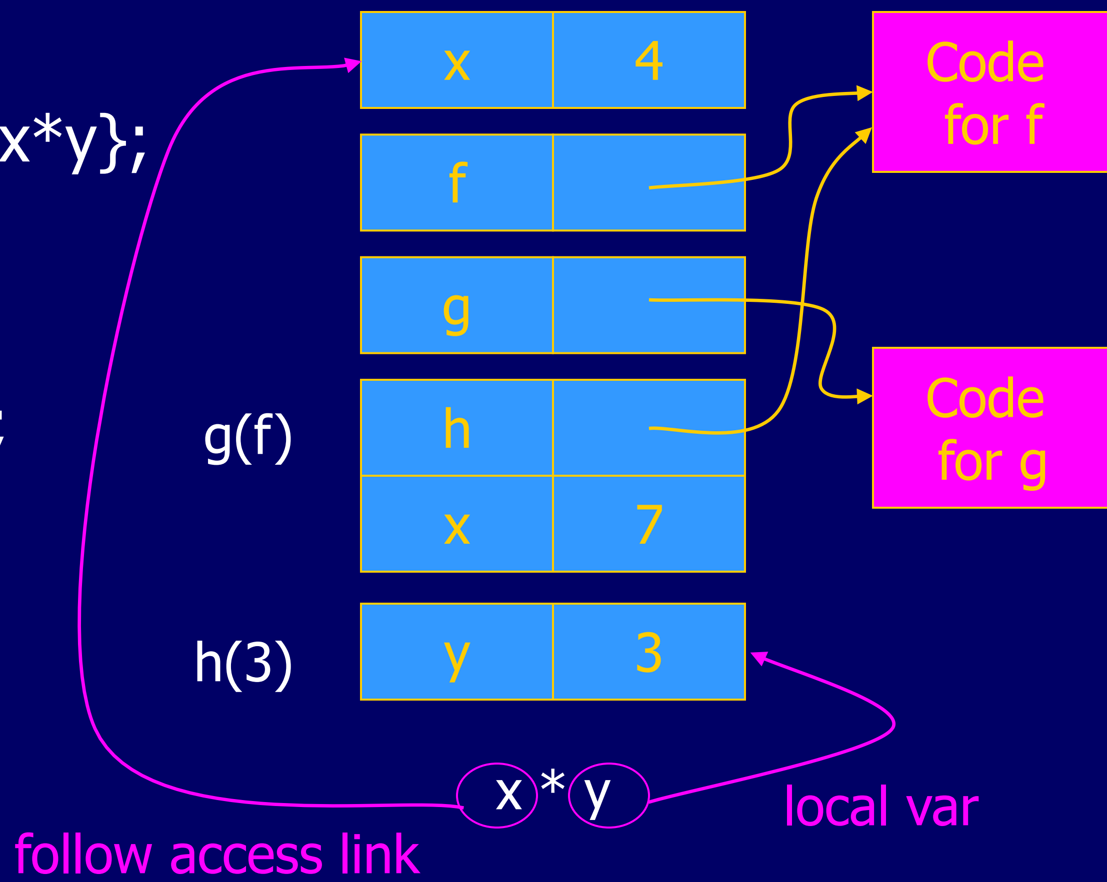
```
let x = 4 in
  let f = fun -> x*y in
    let g = fun h ->
      let
        int x=7
      in
        h(3) + x
    in
    g(f)
```



How is access link for h(3) set?

Static Scope for Function Argument

```
{ var x = 4;
  { function f(y) {return x*y};
    { function g(h) {
          int x=7;
          return h(3) + x;
          };
      g(f);
} } }
```



How is access link for h(3) set?

Result of function call

C:\Documents and Settings\John Mitchell\My Documents\...

```
js> { var x = 4;
    { function f(y) {return x*y;}
        { function g(h) {
                var x = 7;
                return h(3) + x;
            }
            g(f);
} } }
19
js>
```

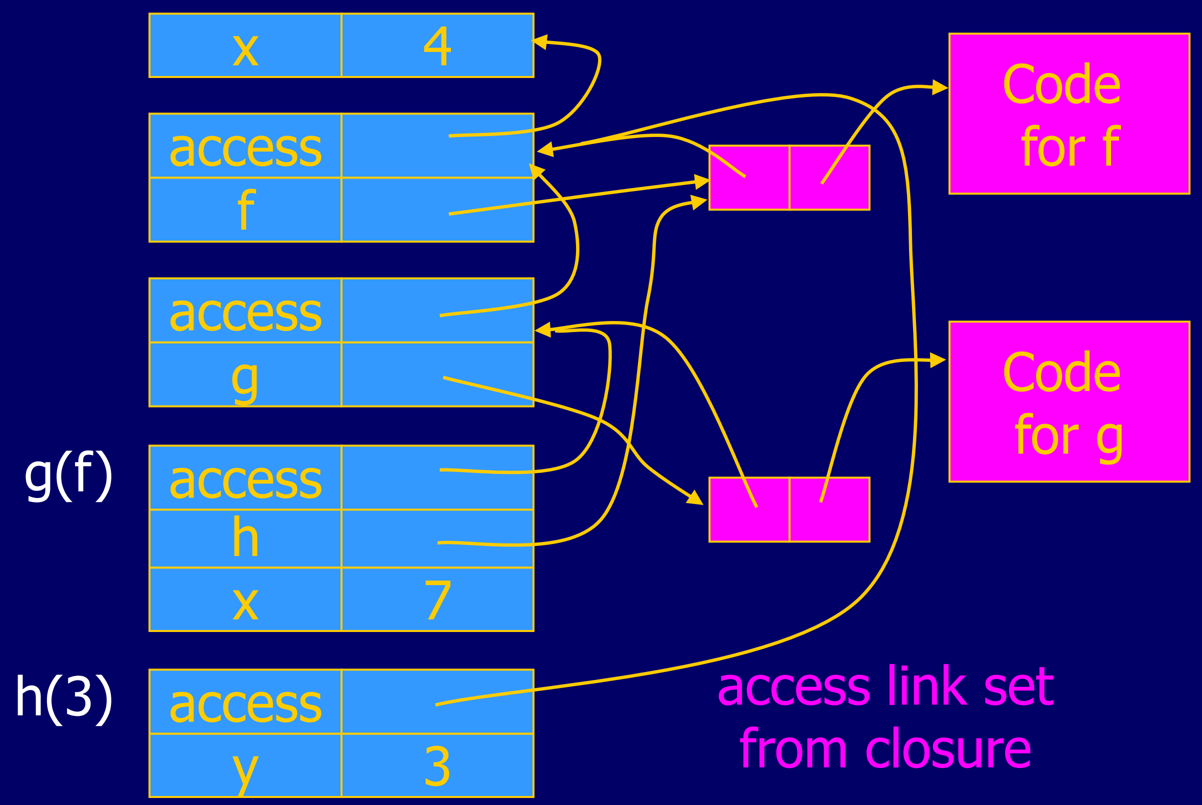
Closures

- Function value is pair *closure* = ⟨*env*, *code* ⟩
- When a function represented by a closure is called,
  - Allocate activation record for call (as always)
  - Set the access link in the activation record using the environment pointer from the closure

Function Argument and Closures

```
let x = 4 in
   let f = fun y->x*y in
      let g = fun h ->
            let
               x=7
            in
               h(3) + x
      in g(f)
```

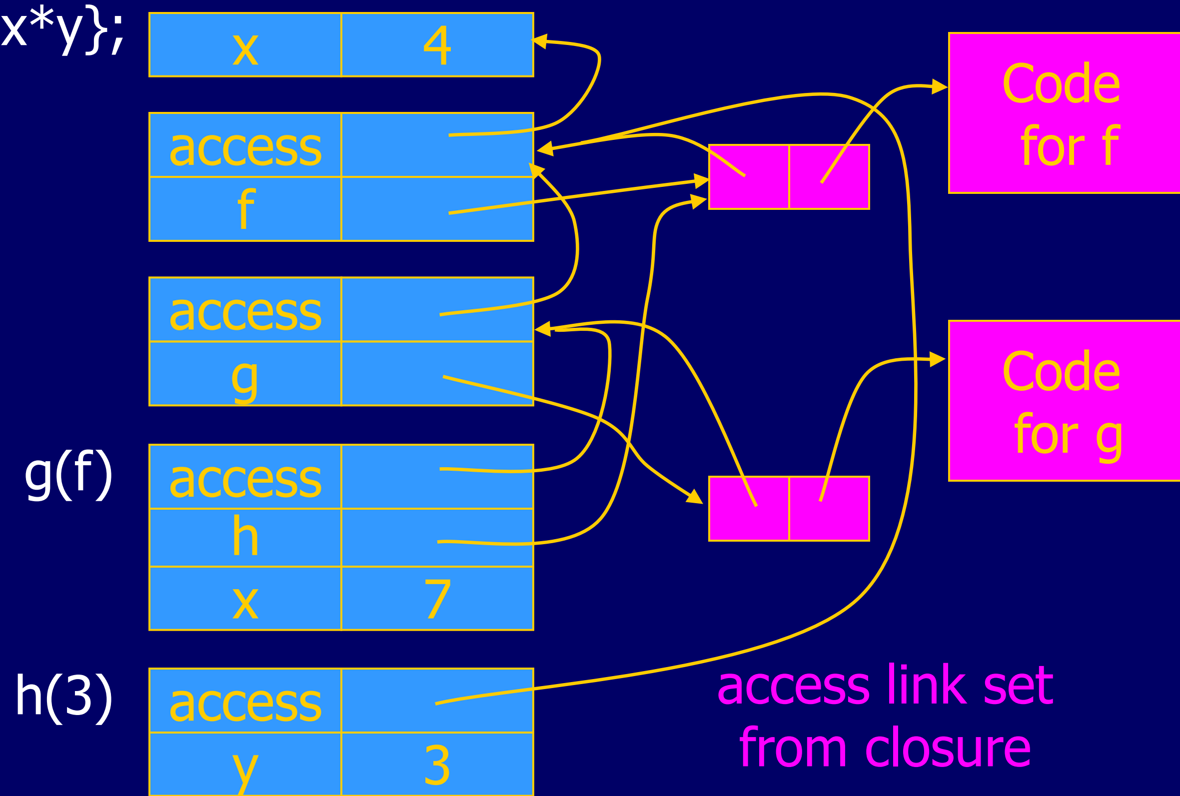
Run-time stack with access links



Function Argument and Closures

Run-time stack with access links

```
{ var x = 4;
  { function f(y){return x*y};
    { function g(h) {
        int x=7;
        return h(3)+x;
      };
      g(f);
}}}
```



Summary: Function Arguments

- Use closure to maintain a pointer to the static environment of a function body
- When called, set access link from closure
- All access links point “up” in stack
  - May jump past activ records to find global vars
  - Still deallocate activ records using stack (lifo) order

Return Function as Result

- Language feature
  - Functions that return "new" functions
  - Need to maintain environment of function
- Example

```
function compose(f,g)
        {return  function(x) { return g(f (x)) }};
```

- Function "created" dynamically
  - expression with free variables

    values are determined at run time
  - function value is closure = ⟨env, code⟩
  - code *not* compiled dynamically (in most languages)

Example: Return fctn with private state

OCaml

```
let mk_counter = fun init  ->
    let count = ref init in
      let counter = fun inc ->
              (count := !count + inc; !count)
      in
        counter
in
   let c = mk_counter 1
     in
   c(2) + c(2)
```

- Function to "make counter" returns a closure
- How is correct value of count determined in c(2) ?

Example: Return fctn with private state

JS

```
function mk_counter (init) {
    var count = init;
    function counter(inc) {count=count+inc; return count};
    return counter};
var c  = mk_counter(1);
c(2) + c(2);
```

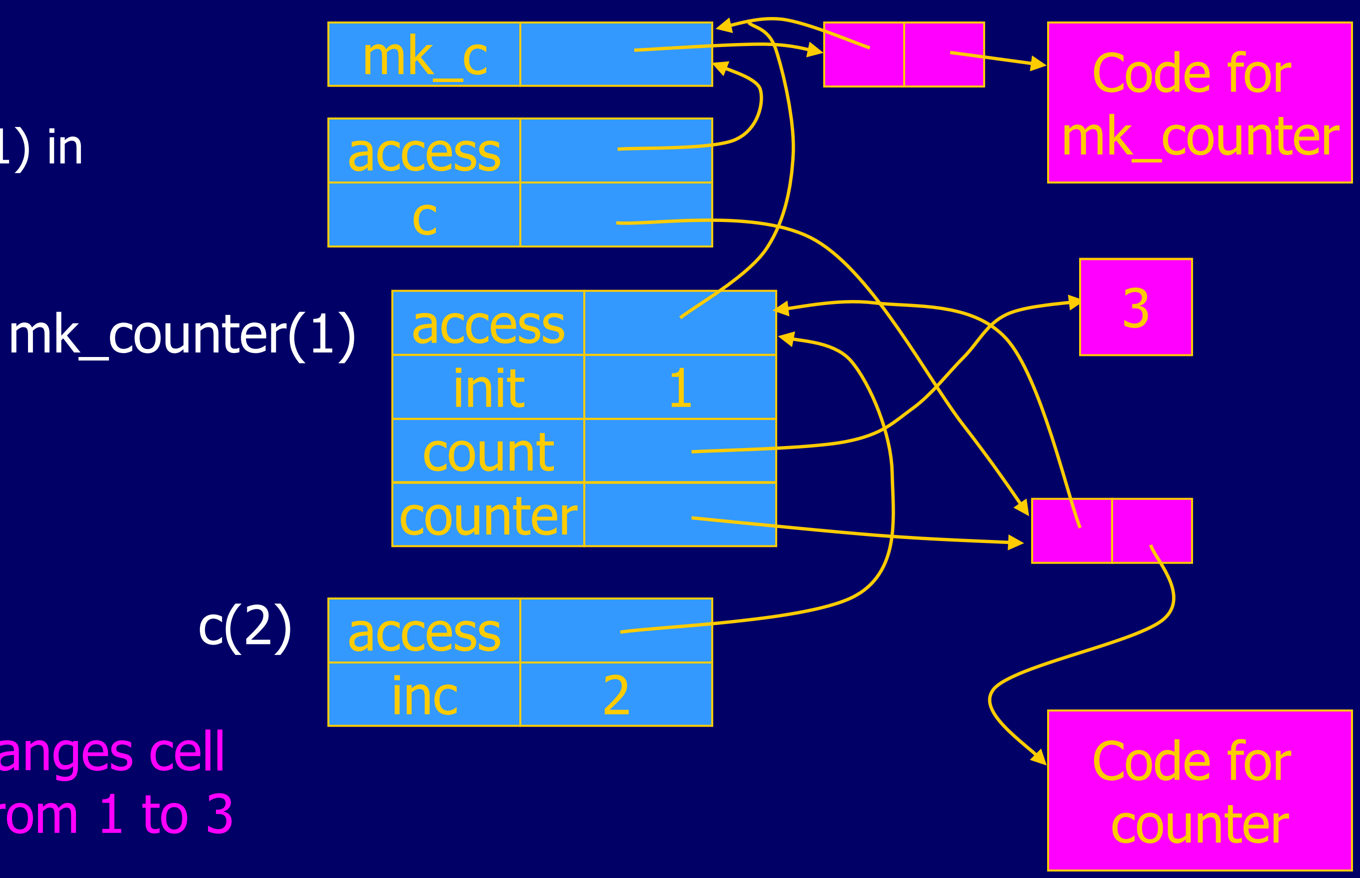
Function to “make counter” returns a closure

How is correct value of count determined in call c(2) ?

Ocaml

Function Results and Closures

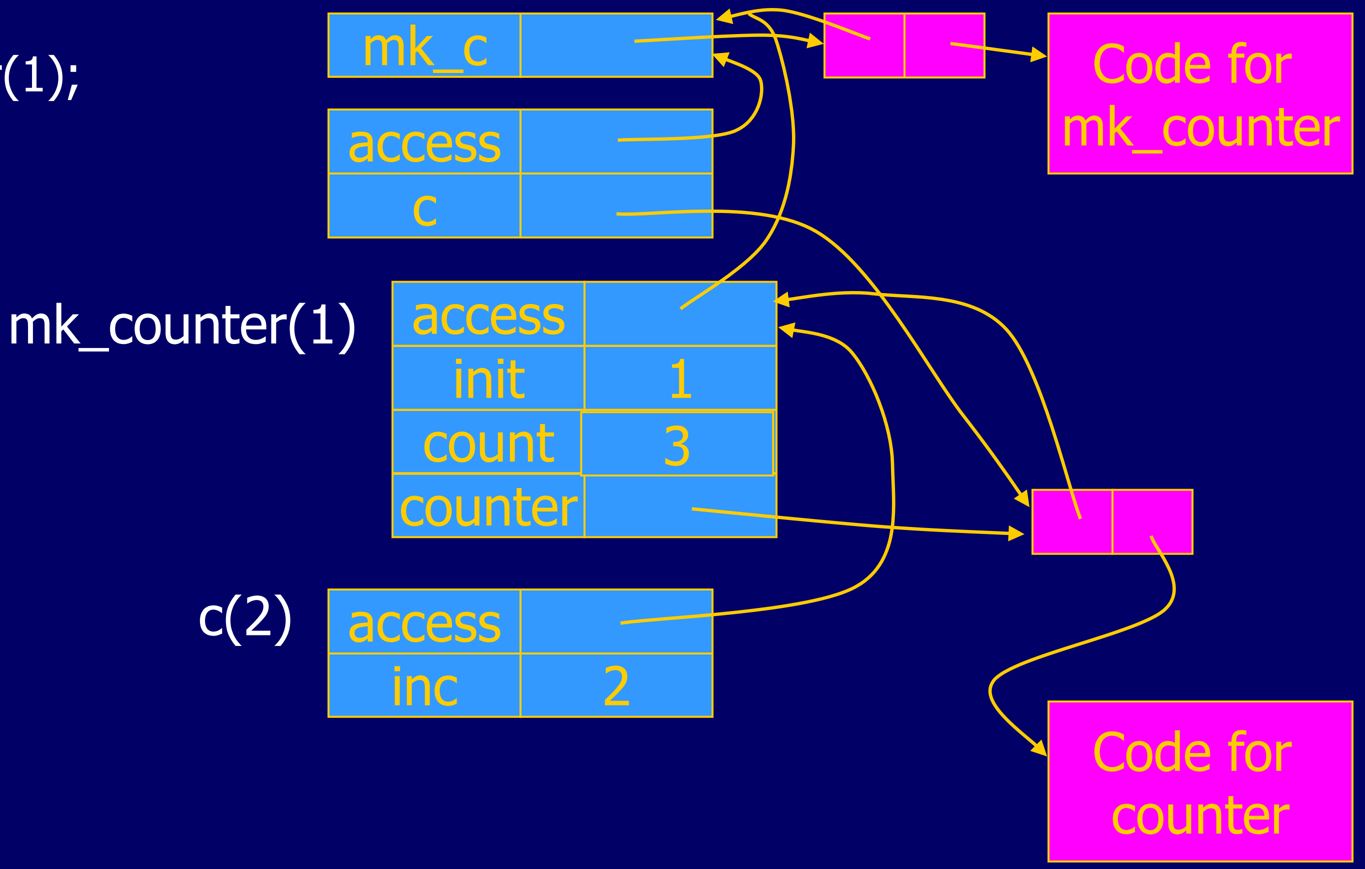
```
let mk_counter =fun init ->
   let count = ref init  in
        let counter = fun inc -> (count := !count + inc; !count)
        in counter
in
let c = mk_counter(1) in
c(2) + c(2)
```



Call changes cell value from 1 to 3

Function Results and Closures

```
function mk_counter (init) {
    var count = init;
    function counter(inc) {count=count+inc; return count};
    return counter};
var c  = mk_counter(1);
c(2) + c(2);
```



Closures in Web programming

- Useful for event handlers in Web programming:

```
function AppendButton(container, name, message) {
    var btn = document.createElement('button');
    btn.innerHTML = name;
    btn.onclick = function (evt) { alert(message); }
    container.appendChild(btn);
}
```

- Environment pointer lets the button’s click handler find the message to display

Simple C Program

```
foo (int y) {
   int x = y ;
   if  (x > 8) {
     int x = y + 1 ;
     x = x  + 1 ;
     }
```

foo(9)

control	
return val	
x	8
y	8
x	9

The C Programming Language

- Designed to allow stack allocation
- Local variables are flattened
- No need for control link
- Permit
  - Nested blocks
  - Passing functions as parameters and return values
- Forbid
  - Nested functions

Summary: Return Function Results

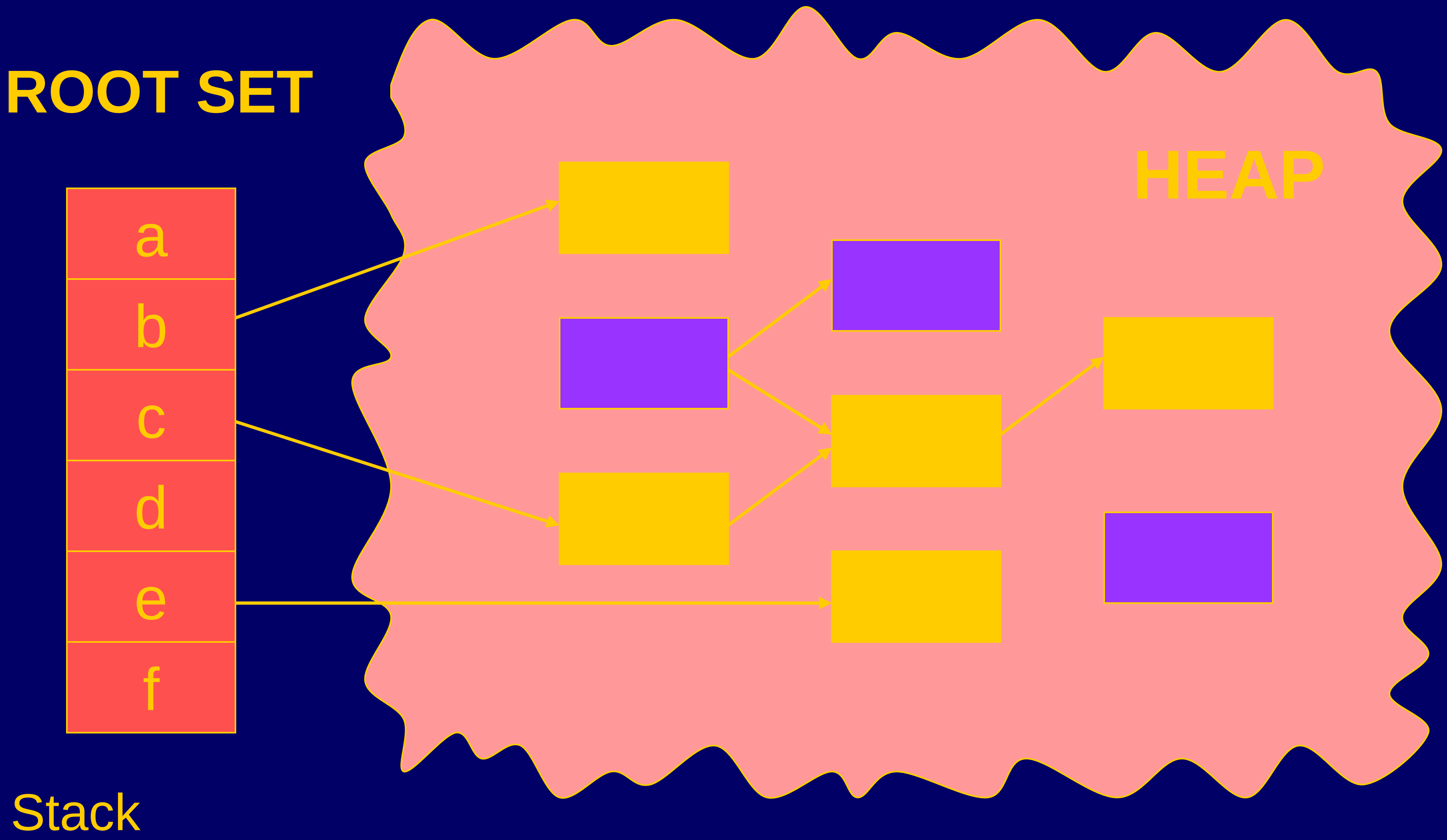
- Use closure to maintain static environment
- May need to keep activation records after return
  - Stack (lifo) order fails!
- Possible "stack" implementation
  - Forget about explicit deallocation
  - Put activation records on heap
  - Invoke garbage collector as needed
  - Not as totally crazy as is sounds

    May only need to search reachable data

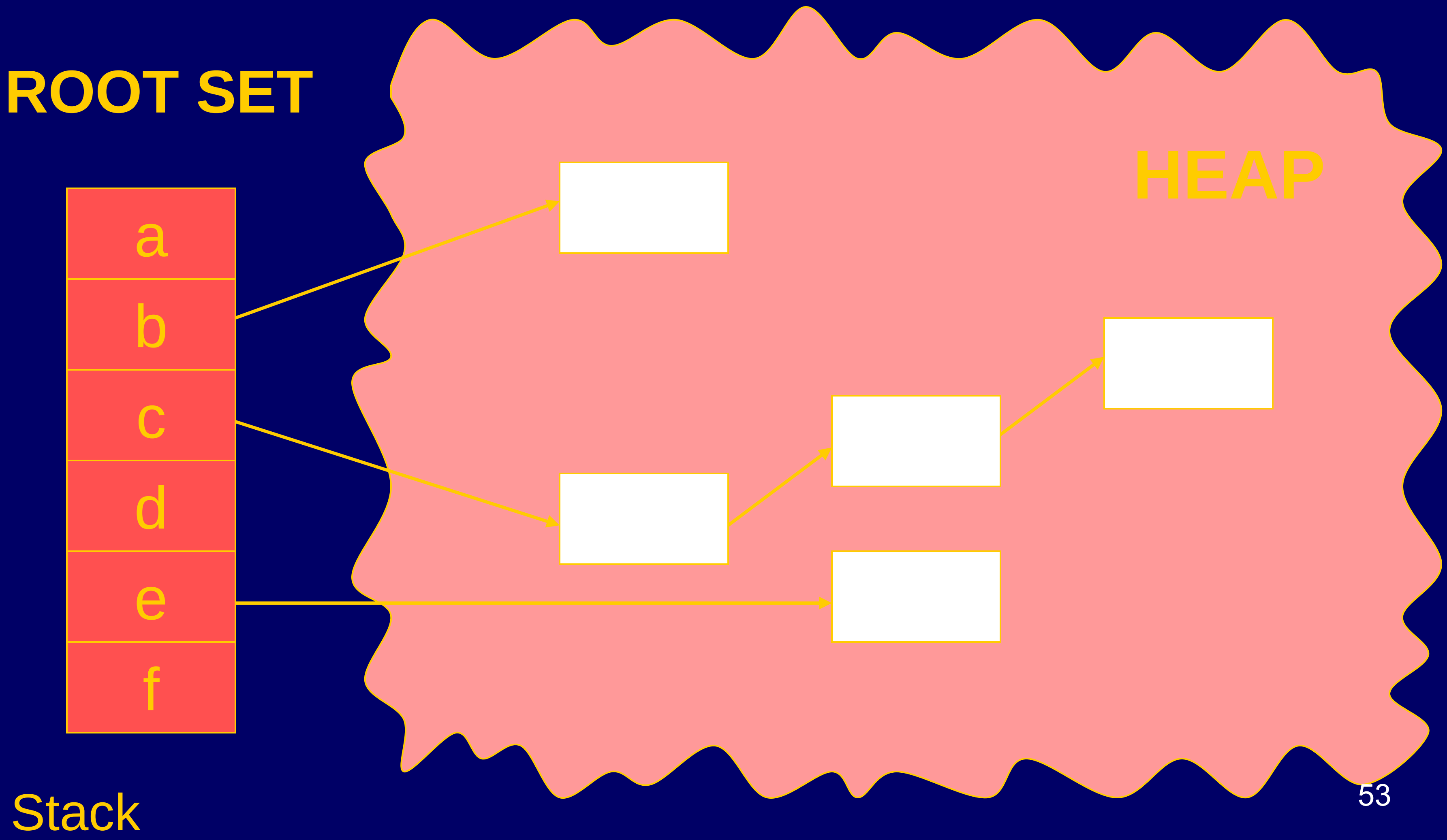
Summary of scope issues

- Block-structured lang uses stack of activ records
  - Activation records contain parameters, local vars, …
  - Also pointers to enclosing scope
- Several different parameter passing mechanisms
- Tail calls may be optimized
- Function parameters/results require closures
  - Closure environment pointer used on function call
  - Stack deallocation may fail if function returned from call
  - Closures *not* needed if functions not in nested blocks

Garbage Collection



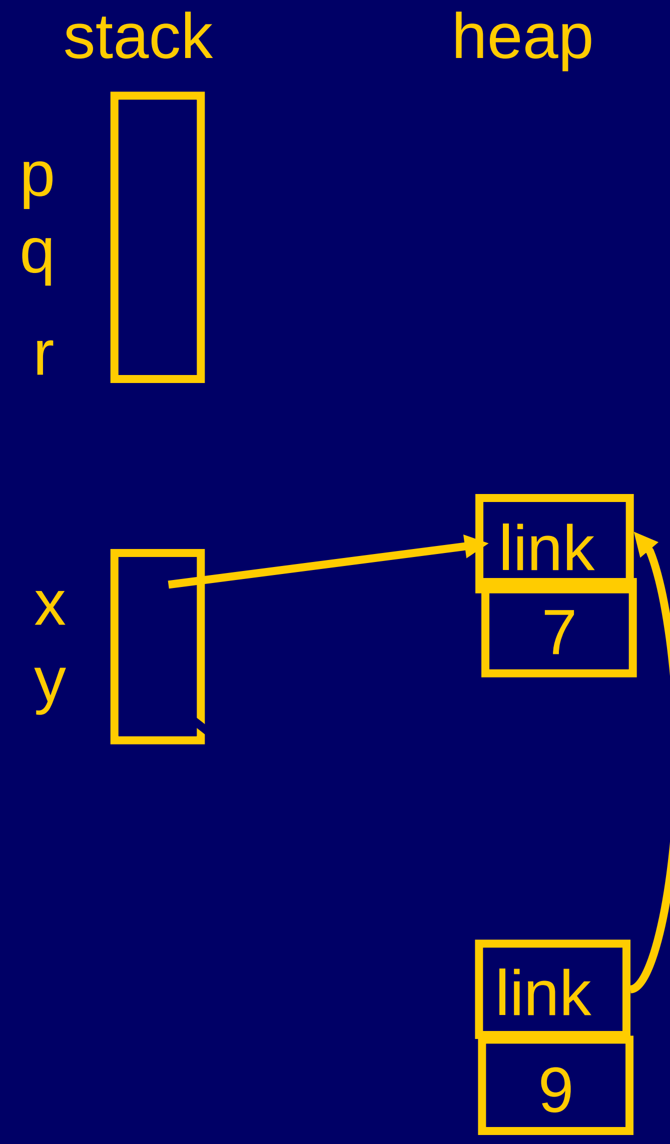
Garbage Collection



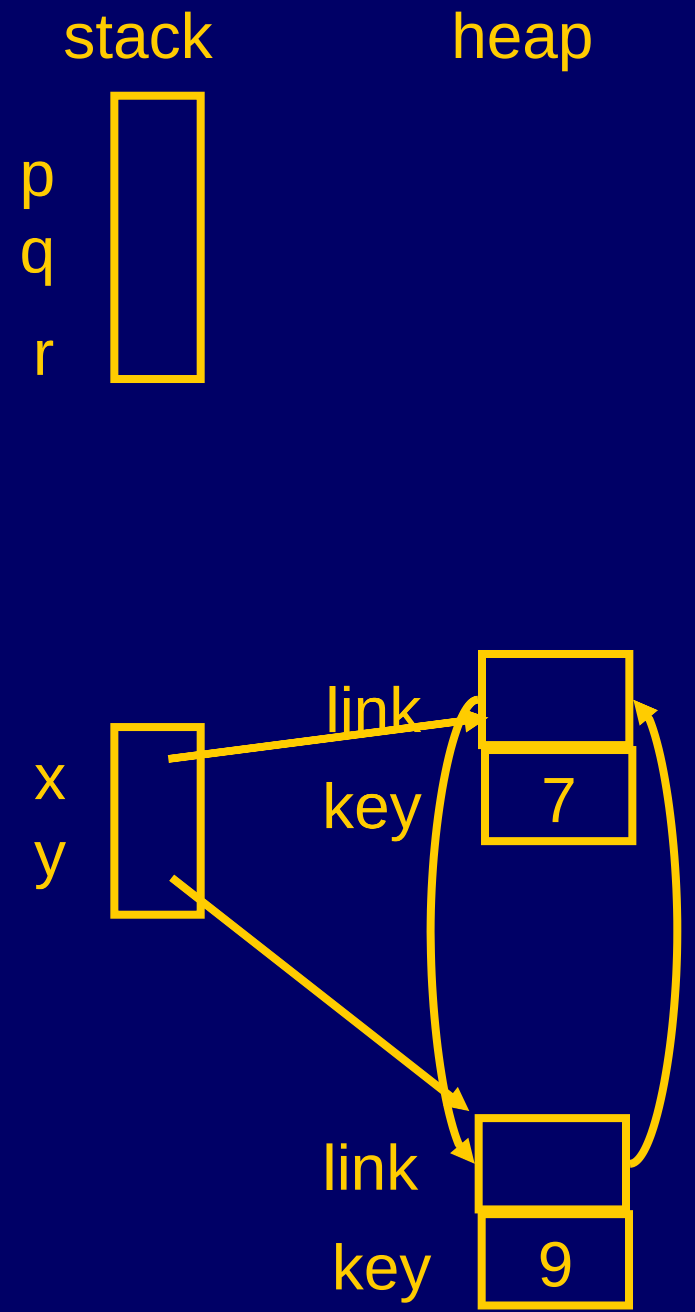
What is garbage collection

- The runtime environment reuse chunks that were allocated but are not subsequently used garbage chunks
  - not live
- It is undecidable to find the garbage chunks:
  - Decidability of liveness
  - Decidability of type information
- conservative collection
  - every live chunk is identified
  - some garbage runtime chunk are not identified
- Find the reachable chunks via pointer chains
- Often done in the allocation function

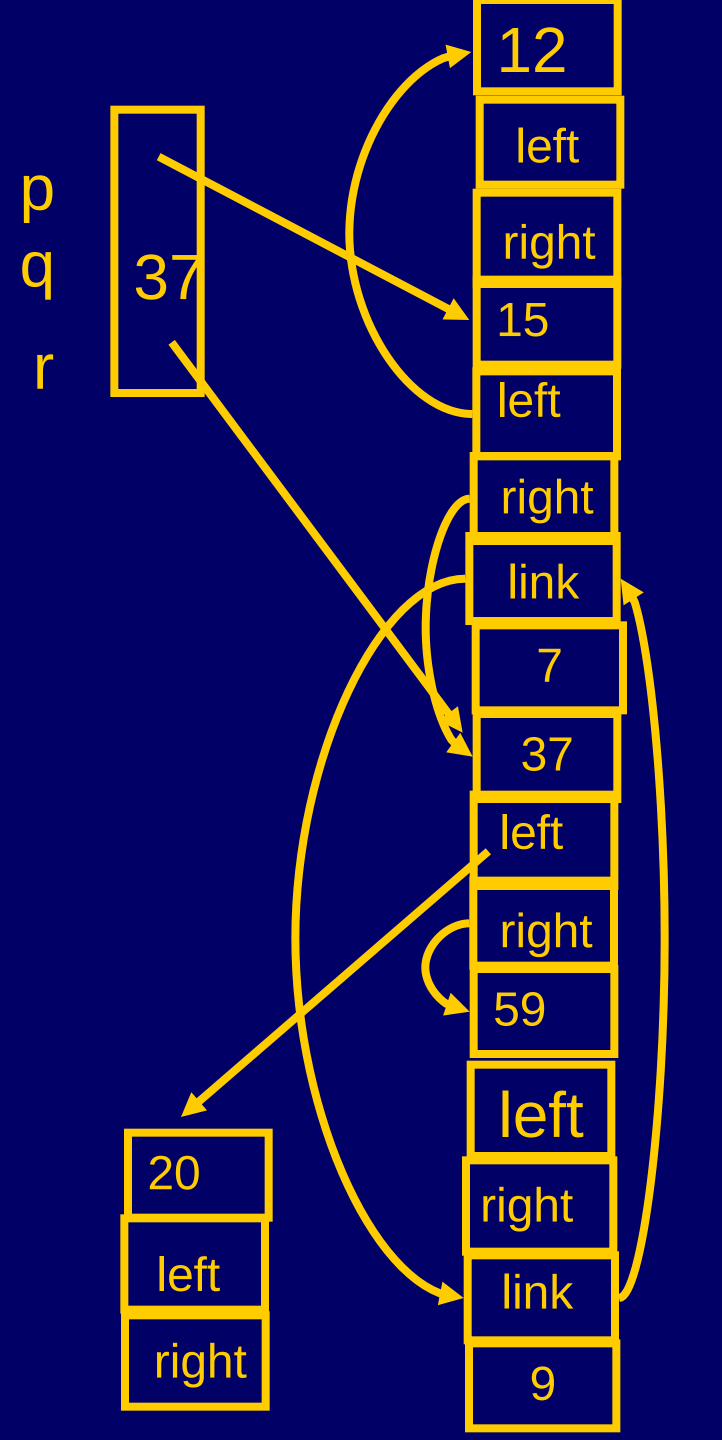
```
typedef struct list  {struct list *link; int key} *List;
typedef struct tree {int key;
                        struct tree *left:
                        struct tree *right} *Tree;
foo() {    List x = cons(NULL, 7);
    List y = cons(x, 9);
   x->link = y;
     }
void main() {
  Tree p, r; int q;
  foo();
  p = maketree();   r = p->right;
  q= r->key;
  showtree(r);}
```



```
typedef struct list  {struct list *link; int key} *List;
typedef struct tree {int key;
                     struct tree *left:
                     struct tree *right} *Tree;
foo() {    List x = cons(NULL, 7);
    List y = cons(x, 9);
   x->link = y;
    }
void main() {
  Tree p, r; int q;
  foo();
  p = maketree();   r = p->right;
  q= r->key;
  showtree(r);}
```



```
typedef struzct list  {struct list *link; int key}
*List;
typedef struct tree {int key;
                                struct tree *left:
                                struct tree *right} *Tree;
foo() {    List x = create_list(NULL, 7);
    List y = create_list(x, 9);
   x->link = y;
     }
void main() {
  Tree p, r; int q;
  foo();
  p = maketree();   r = p->right;
  q= r->key;
  showtree(r);}
```



Garbage Collection Techniques

- Tracing
  - Scan the reachable heaps from the root
  - Release unreachable elements
  - Cost proportional to reachable heap
- Reference Counting
  - Maintain a counter of references to each chunk of memory
  - The compiler generates the update code for references when pointers are manipulated
  - Release objects with zero reference counter
  - Constant cost

Mark-and-Sweep(Scan) Collection

- Mark the chunks reachable from the roots (stack, static variables and machine registers)
- Sweep the heap space by moving unreachable chunks to the freelist (Scan)

The Mark Phase

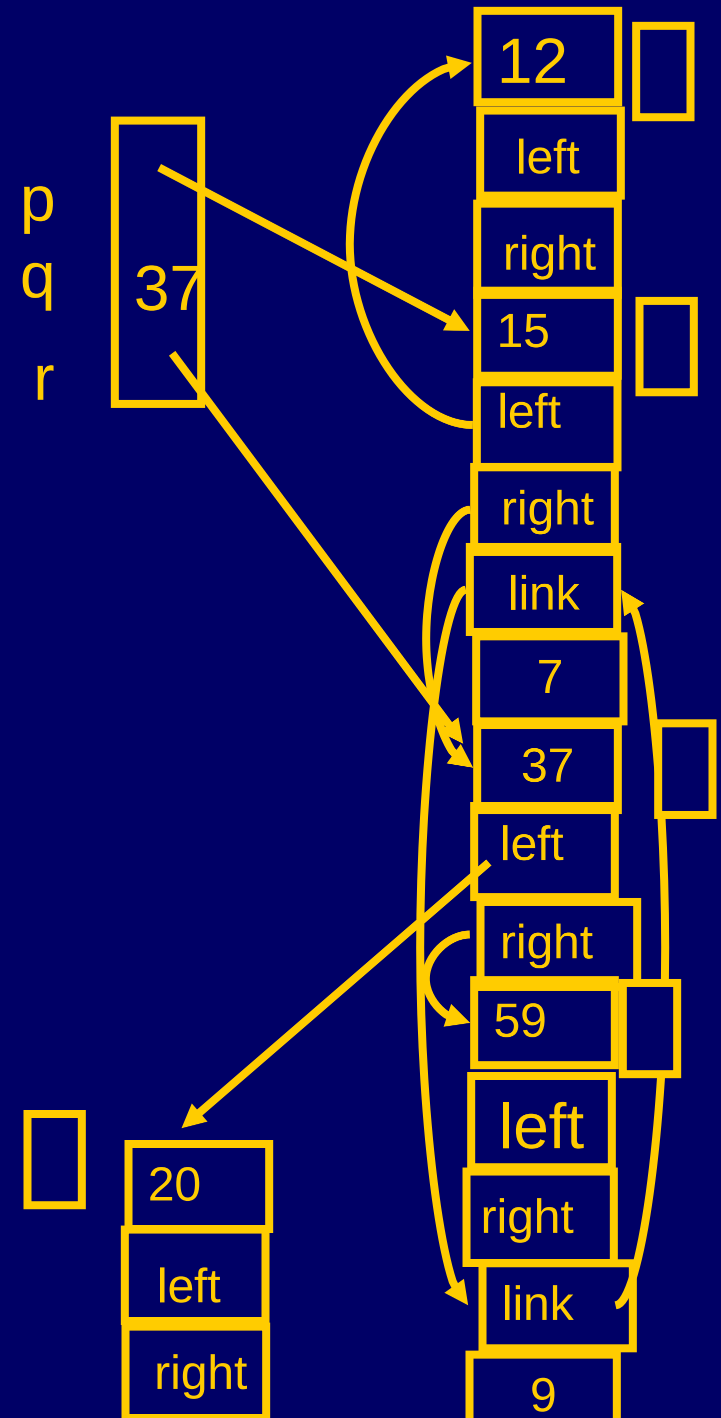
```
for each root v
  DFS(v)

function DFS(x)
  if x is a pointer and chunk x is not
marked
          mark x
          for each reference field f_i of
chunk x
             DFS(x.f_i)
```

The Sweep Phase

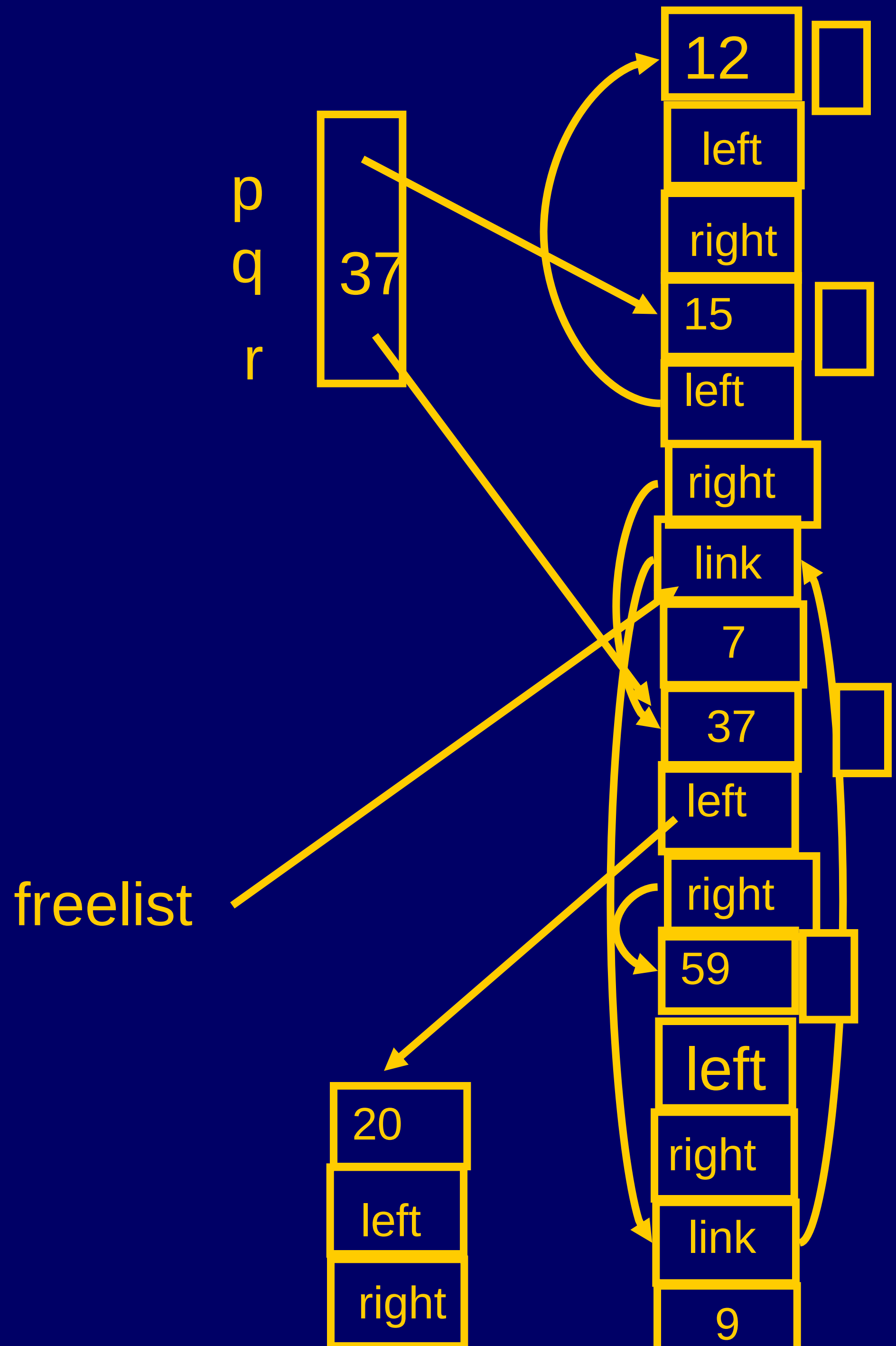
```
p := first address in heap
while p < last address in the heap
        if chunk p is marked
                unmark p
        else let f1 be the first pointer reference field in
p
                p.f1 := freelist
                freelist := p
        p := p + size of chunk p
```

Mark

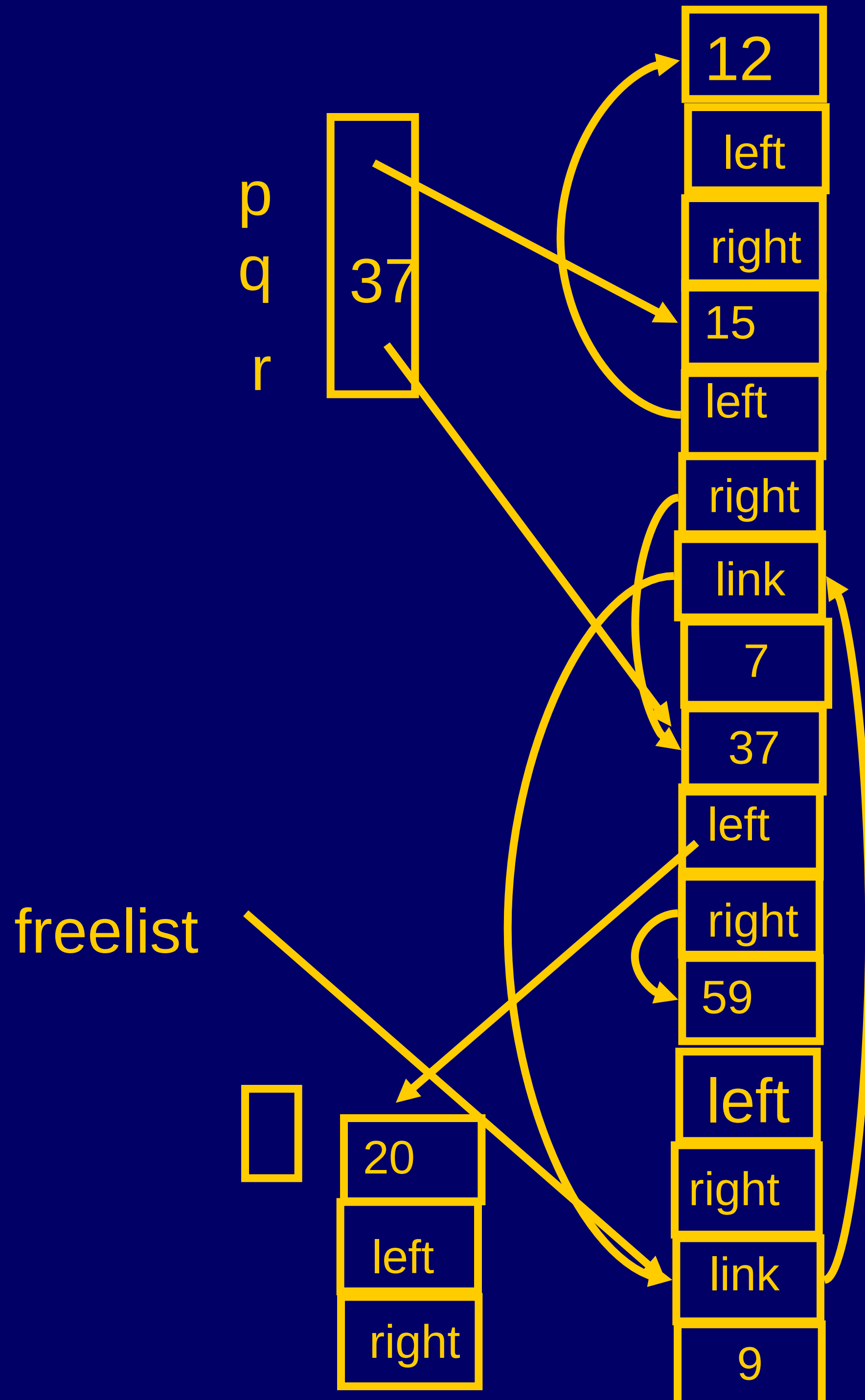


p
q
r
37
12
left
right
15
left
right
link
7
37
left
right
59
left
right
link
9
20
left
right

Sweep



p
q
r
37
12
left
right
15
left
right
link
7
37
left
right
59
left
right
link
9
freelist
20
left
right



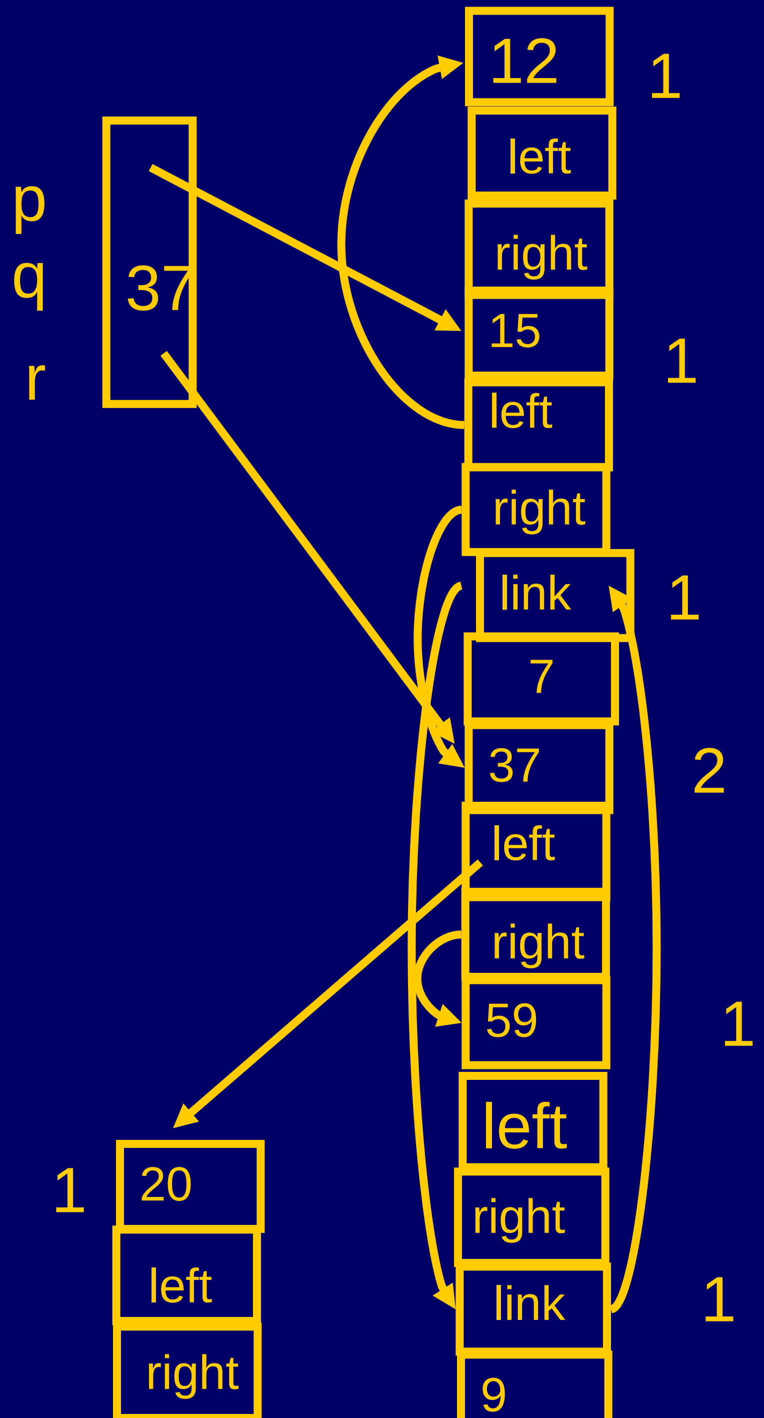
12
left
right
p
q
37
r
15
left
right
link
7
37
left
right
59
freelist
left
right
link
9
20
left
right

Cost of GC

- The cost of a single garbage collection can be linear in the size of the store
  - may cause quadratic program slowdown
- Amortized cost
  - collection-time/storage reclaimed
  - Cost of one garbage collection
    - $c_1 R + c_2 H$
  - H - R Reclaimed chunks
  - Cost per reclaimed chunk
    - $(c_1 R + c_2 H)/ (H - R)$
  - If $R/H > 0.5$
    - increase H
  - if $R/H < 0.5$
    - cost per reclaimed word is $c_1 + 2c_2$ ~16
  - There is no lower bound

Reference Counting

- Maintain a counter per object
- The compiler generates updates for counters
- Release object with zero counters
- Cannot reclaim cyclic objects
-



p
q
r
37
12
left
right
15
left
right
link
7
37
left
right
59
left
right
link
9
20
left
right
1
1
1
2
1
1
1

Garbage Collection vs. Explicit Memory Deallocation

- Faster program development
- Less error prone
- Can lead to faster programs
  - Can improve locality of references
- Support very general programming styles, e.g. higher order and OO programming
- Standard in ML, Java, C#, Javascript
- Supported in C and C++ via separate libraries

- May require more space
- Needs a large memory
- Can lead to long pauses
- Can change locality of references
- Effectiveness depends on programming language and style
- Hides documentation
- More trusted code

Summary

- Runtime memory management is crucial for functionality and correctness
- Lexical scope is natural
  - Becomes tricky with higher order functions
  - Closures
- Garbage Collection permits general programming style